Properties of Diamond Dust Type Ice Crystals Observed in Summer Season at Amundsen-Scott South Pole Station, Antarctica

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Abstract

The properties of diamond dust type ice crystals were studied from replicas obtained during the 1975 austral summer at South Pole Station, Antarctica. The time variation of the number concentration and shapes of crystals, and the length of the c -axis, the axial ratio (c/a) and the growth mode of columnar type crystal were examined at an air temperature of -35°C .

Columnar type crystals prevailed, but occasionally more than half the number of ice crystals were plate types, including hexagonal, scalene hexagonal, pentagonal, rhombic, trapezoidal and triangular plates. A time variation of two hour periodicity was found in the number concentration of columnar and plate type crystals. When the number concentration of columnar type crystals decreased, the length of the c -axis of columnar type crystals also decreased. When the number concentration of columnar type crystals increased, the length of the c -axis of the crystals also increased. There was sufficient water vapor to grow these ice crystals in a supersaturation layer several tens to several hundred meters above the surface.

The growth mode of columnar type crystals was different from that of warm and cold region columns reported by Ono (1969). The mass growth rate was $6.0 \times 10^{-10} \text{ gr} \cdot \text{sec}^{-1}$, and was similar to that obtained in cold room experiments by Mason (1953), but less than that found in field experiments by Isono, *et al.* (1956).

The plate type crystals prevailed occasionally at an air temperature of -35°C , at which the sheath, hollow and solid prism (column) usually prevail. An important question arises with respect to the crystal habit with air temperature lower than -22°C in the $Ta-\Delta\rho$ diagram consolidated by Kobayashi (1961).

1. Introduction

Ice crystal observations carried out till the present have generally been limited to the conditions of ice fog on the ground (Ito (1953), Thuman and Robinson (1954), Sakurai (1968, 1969), Ohtake (1970)), and cirrus and cumulus clouds aloft using observation aircraft (Mossop, *et al.* (1967, 1969), Ono (1969, 1970)). Several of these studies were *in situ* and did not treat

the time variations of number concentration, crystal shapes, growth mode, mass growth rate of the ice crystals.

The authors made ice crystal observations in the austral summer season throughout a thirty day period in January and February, 1975 at Amundsen-Scott South Pole Station, Antarctica (Kikuchi and Hogan, 1976). On 29 January, 1975, we experienced a precipitation of diamond dust type ice crystals under a condition of 22°

and 46° haloes, beneath an otherwise fine blue sky. Although the precipitation intensity varied greatly, the precipitation continued throughout the day. Detailed observational results will be described, especially addressed to crystal shapes, time variations of number concentration of ice crystals, growth mode and mass growth rate of these ice crystals in the free atmosphere.

2. Technique employed

The geographical altitude of Amundsen-Scott South Pole Station is 2,804 m and the mean surface air temperature in January is approximately -30°C . Conventional radiosonde observations are made twice (00Z, 12Z) daily at the station during the summer season. Proper circumstances often exist for observations of ice crystals which may form by spontaneous nucleation in the free atmosphere. The low temperatures and extremely dry air found near the snow surface limit the accuracy of humidity measurement; calculation from radiosonde data often indicates that air saturated with respect to ice and sometimes with respect to liquid water is present in the 650~550 mb layers (100~1,000 m above the surface). The presence of these saturated layers was verified by dry ice seeding experiments during this observation period by the authors (Kikuchi and Hogan, 1976).

Precipitating ice crystals were collected near the station at the entrance to the helium storage hut next door of balloon launching site. This hut was unheated and had a compacted snow floor. This allowed examination of the collected crystals without significant sublimation or melting during the short period between collection and examination.

A polarizing microscope was used to make color photographs of the shapes of ice and snow crystals, and to determine the principal axis (c -axis) of the crystals at approximately 10 minute intervals. Simultaneously, the crystals were collected by sedimentation and replicated on 25×75 mm glass slides coated with 0.5% Formvar solution at 5 or 20 minute intervals. The collection of the diamond dust type ice crystals was by an interception technique at the same time intervals. This analysis is based on examination of these formvar replicas.

The diamond dust crystals were quite small and the crystal shapes were not identifiable by eye. After the collected diamond dust crystals had been brought back to our laboratory, the slides were scrutinized carefully by 1 mm width

segments under an ordinary transmitted light microscope and almost all crystals found in the field of view of the microscope were photographed. The negatives were examined in a film editor. The number of crystals were counted and the length and width of the columnar type crystals were measured on the projected glass surface. The total magnification of the microscope and equipment was from 100 to 200. The total number of ice crystals on each glass slide was from several tens, to a few thousand individual crystals.

3. The shapes of ice crystals

A surface air temperature during this observation period was from -37°C to -35°C ; the air temperature at the inversion top a few tens meters aloft was -34°C . As expected at these temperature ranges (Kobayashi, 1961), the predominant shape of the ice crystals was columnar type as shown in Fig. 1(a) and (b). An average value of the axial ratio of c - and a -axes, that is (c/a), was 2.5~5.5. However, as seen in these figures, there were many examples of a larger (c/a) of 10 or more. This was also found in the observations of Klinov (1960) and Shimizu (1963), and in experimental results by Kobayashi (1965). It was also quite common to find minute hexagonal plate type crystals, as shown in Fig. 1(c). Scalene hexagonal and pentagonal shapes as shown in Fig. 1(d), (e), (f) and (i) were more common. Sometimes a few trapezoidal, triangular and rhomboidal shapes were discovered (Fig. 1(g), (h) and (j)).

Almost all shapes described above have been reported by Klinov (1960). These observations verified the existence of the possible shapes of the basal faces, except for surface structures in the basal faces, examined in seeding experiments by Yamashita (1973). Square form crystals were found frequently as shown in Fig. 1(k) and (l); it is possible to recognize a pair of dark parts at the upper and lower sides in these photographs. These dark parts are estimated to be the (1010) and ($\bar{1}100$) planes; that is, these crystals are a column type which are depressed vertically in the (01 $\bar{1}0$) plane. There were other crystals of square form without a pair of dark parts within the population. It is very difficult to conclude from examination of replicated ice crystals on a glass slide that these are a type of square ice crystal.

At this stage of ice crystals, there have not been recognized an early stage of growth of

Fig. 1 Typical shapes of diamond dust type ice crystals.

Fig. 2 Time variations of number concentration of ice crystals and surface air temperature.

“peculiar shaped” snow crystals.

4. Time variation of number concentration of ice crystals

Fig. 2 shows the time variation of the number concentration of ice crystals. In this figure, white, black and striped histograms denote the number concentration of column (Fig. 1(a) and (b)), hexagonal plate (Fig. 1(c)) and other plates, including scalene hexagonal, triangular, and so on (residual figures in Fig. 1 except (a), (b) and (c)), respectively. This figure indicates that the number concentration of ice crystals has a time variation peaking at two hour intervals. Within this time variation, there are characteristic increases of column type crystal (for instance, at 10:30 and 14:40) and of plate type crystals (for instance, at 13:45 and 16:40).

The air temperature changed at the surface, from -37°C at the beginning to -35°C at the end of observation. Tracing the temperature record, the air temperature increased gradually to -35°C and wind direction and velocity were nearly constant at 90° and 10 knots. Under this nearly steady condition, it is worthy of attention that more than half of the number concentration was occupied frequently by the plate type crystals.

An increase of the number concentration around 15:00 may result from the appearance of the cirrus clouds, which were reported in routine observations by the NOAA meteorologist in charge. At that time he reported one tenth

of the altostratus clouds at 800 feet above the surface as the lowest layer clouds (L.L. 1 As 8), and one tenth of the cirrus clouds at 10,000 feet above the surface as the second layer clouds (S.L. 1 Ci 100). Hogan (1975) hypothesized that the existence of cirrus cloud bands at higher altitude, above the saturated layers, is an important factor initiating ice crystal falls. More smaller ice crystals settling into the saturated layers serve to nucleate columnar ice crystals, which then precipitate to the surface. No direct correlation, however, between surface precipitation and the existence of cirrus clouds was attempted during this period.

5. Time variation of the length of c -axis and the axial ratio (c/a) of ice crystals

At the beginning of the observation period, almost all crystals were the column type as shown in the first histogram of Fig. 2. The frequency distributions of the length of c -axis and axial ratio (c/a) of the replicas obtained of that time are shown in Fig. 3. The total number of ice crystals replicated on the glass slide was 1237, and the mean length of c -axis and mean (c/a) was $90.3\text{ }\mu\text{m}$ and 4.9, respectively. The maximum values were $220\text{ }\mu\text{m}$ and 18.5, respectively. These values were clearly different from that of ice crystals in supercooled fog observed by Sakurai (1968). In his case, when the ice crystals coexisted with supercooled fog droplets, the mean lengths along c - and a -axes of ice crystals were nearly the same (approximately $60\text{ }\mu\text{m}$), and

Fig. 3 Number and percentage frequencies of the length of c-axis and axial ratio (c/a).

Fig. 4 Time variation of frequency of the length of c-axis. D , M and N mean the mode and mean values of the length and total number measured.

when the supercooled fog droplets disappeared, the axes remained the same. In this case, the sizes were smaller than that described above, approximately $20 \mu\text{m}$.

The time variations of the length of c-axis and axial ratio (c/a) are shown in Figs. 4 and 5,

respectively. In these figures, D , M and N denote the mode and mean values and the measured number, respectively. As shown in both figures, the time variations were very large. At the 10:30, the maximum and mode lengths were more than $200 \mu\text{m}$ and more than $100 \mu\text{m}$.

Fig. 5 Time variation of frequency of the axial ratio (c/a). D , M and N mean the mode and mean values of the ratio and total number measured.

Fig. 6 Time variation of the mean length of c -axis versus axial ratio (c/a).

However, at the time of 11:30, the lengths were only 120 μm , and less than 40 μm . The maximum and mode values changed from 160 μm and 40 μm at 13:45 to 220 μm and 110 μm at 14:40. The same tendency was recognized at the same time in Fig. 5.

Combining the informations in Figs. 4 and 5, a new figure relating the mean c -axis and the mean axial ratio (c/a) was drawn as Fig. 6. In this figure, black dots and white circles show the values at the morning and afternoon, and the

figures nearby the values are the observation time. As described previously, the values of the c -axis and axial ratio (c/a) from 10:30 to 11:30 were decreasing constantly, and this period corresponded with that of the decreasing of the number concentration of columnar type of ice crystals. In turn, both values increased from 13:45 to 14:40, and this period inversely corresponded with that of the increasing of the number concentration of columnar type of ice crystals.

The gradient of mean length of c -axis versus axial ratio (c/a) was consistent in both periods, and this gradient reached the value obtained by Sakurai (1968) on ice fog at Asahikawa, Hokkaido. This means that the time variation of the length of a -axis was less than that of the c -axis. However, the value of axial ratio (c/a) from 14:40 to 15:40 did not change. Therefore, in this period the rate of change of both lengths of the c - and a -axes was constant. Around at 17:00 neither the length of c -axis nor the value of (c/a) showed any change of their values.

6. Growth mode of relatively small columnar type of ice crystals

Examinations of growth mode, especially the lengths of c - and a -axes, axial ratio (c/a), and so on, of columnar type of ice crystals has been carried out by several workers. Kikuchi (1968) treated single bullet and combination of bullet type crystals, and Iwai (1973) examined needle, sheath and column type crystals. Both types of ice crystals examined were relatively long; in the former case, a size range of the c -axis of bullet was from 0.1 mm to 1.5 mm, and in the latter, was from 0.1 mm to more than 2.0 mm. Ono (1969, 1970) examined the shapes, riming properties and growth mode of ice crystals shorter than the previous data in natural clouds. His data shows, in both cases of warm and cold region columns, the length of c -axis was from 200 μm

to 600 μm , and the maximum length of the a -axis was approximately 90 μm . It is apparent that these size ranges are relatively too large to consider as early stage of crystal growth of columnar type of ice crystals.

Fig. 7(a) and (b) show the relation between a - and c -axes of column type crystals alone, when the columnar type of ice crystals prevailed at 10:30 and 14:40, as described previously in Figs. 2, 4, 5 and 6. In this examination, we did not measure the length of the crystal less than 10 μm of a - and c -axes of crystal. In small sized crystals, less than 10 μm , the crystal shapes collected and replicated on glass slides are globular and are difficult to define the c -axis. Almost all columnar crystals were solid columns, which were confirmed by simultaneous measurement of the unreplicated crystals using a polarizing microscope. The greater part of crystals were distributed and concentrated inside of sheath region separated and drawn by Ono (1969). A few percents were distributed inside of warm and cold column region at 10:30. In the case of 14:40 in Fig. 7, although more were distributed inside of column region, the great number were inside of the sheath region. A limit of the maximum length of the a -axis was 50 μm even in the column region, and this 50 μm coincided with the boader line between sheath and column regions which the length of c -axis was longer than 200 μm . The 50 μm length of the a -axis coincided with

Fig. 7 Relation between lengths of c - and a -axes of columnar type ice crystals when columnar type crystals prevailed in diamond dust.

Fig. 8 Relation between lengths of c - and a -axes of columnar type ice crystals when plate type crystals prevailed in diamond dust.

that obtained by dry ice seeding in a supercooled fog by Isono, *et al.* (1956).

Fig. 8(a) and (b) show the same relation of column type as Fig. 7 except that observation times when the plate type of ice crystals prevailed were at 13:45 and 16:40. The distributions of relation between both axes were scattered more than Fig. 7, and shifted from sheath to column region as compared with Fig. 7 in which column type crystals prevailed. The length of c -axis was shorter than that of Fig. 7, especially in the case of 16:40.

7. Time cross section of $\Delta\sigma_i$ and air temperature

During the observation period, approximately 10 hours, the surface air temperature changed only 2°C , from -37°C to -35°C , as shown in Fig. 2. The crystal shapes observed were column type, relatively long columns, and plate types (hexagonal plates and other plates, including scalene hexagonal and triangular). Occasionally plate types of ice crystals were observed as 50 percent or more of total number of crystals; for instance, at 13:45 and from 16:00 to 18:00, except around 17:00. A time cross section of $\Delta\sigma_i$ (percent of supersaturation with respect to ice) and air temperature was made up (Fig. 9) based on the routine radiosonde data made twice a day.

As seen in Fig. 9, the distribution curves of air temperature (dashed lines) and $\Delta\sigma_i$ (solid

Fig. 9 Time cross section of air temperature and supersaturation with respect to ice ($\Delta\sigma_i$) at Amundsen-Scott South Pole Station.

lines) were nearly constant, and both factors had stratified throughout the observation period from 08:00 to 18:00. Generally at the South Pole Station in summer season, the surface temperature inversion is not exceptionally strong because of the continuous sunshine. At observation time, 12:00 on the 29th, the surface temperature inversion was only 2°C ; that is, the temperature of the inversion top was -34°C . The top of the moist layer was around 550 mb, approximately 1,500 m above the surface. The air was supersaturated with respect to ice only at 200 m above the surface. Above this height, a deep super-

saturation was maintained throughout the observation period. Therefore, almost all types of ice crystals grew in the temperature range from -37°C to -34°C and the ice supersaturation range less than 40%. However, as it is said that radiosonde data relating to humidity measurements at lower air temperature around -40°C sometimes have a marginal error more than $\pm 20\%$, it should be thought that lower atmosphere at this time was a supersaturation with respect to ice or water saturation, because the external shapes of ice crystals were very sharp. Furthermore, sometimes at South Pole area, it have been confirmed the existence of water saturation layer at 20 m above snow surface (Kikuchi and Hogan, 1976).

Kobayashi (1961) made up a T_a - $\Delta\rho$ diagram for snow crystal habit. He emphasized that even though the temperature could be decreased from -22°C to -90°C , any changes in the crystal habit was impossible and the diagram was consolidated under the single-crystalline edifice (Kobayashi, 1965, 1975). According to his opinion, the crystal habit at lower than the temperature (T_a) of -22°C was not plate types but prism (column) or sheath types as seen in the diagram. Therefore, there is an important difference between our observation result and his T_a - $\Delta\rho$ diagram, especially with respect to crystal habit. Recently, Gonda (1977) reported that the habit and the growth feature of small ice crystals of less than $50\text{ }\mu\text{m}$ diameter depended not only on the temperature and the degree of supersaturation, but also on the diffusion coefficient of water vapor, the thermal conductivity of the carrier gas, and the size of crystals.

8. Mass growth rate of columnar type of ice crystals

As described previously, the vertical distributions of air temperature and supersaturation throughout the observation period was linearly stratified. This facilitates calculation of mass growth rate of the columnar type of crystals based upon the diffusion of water vapor. Although the examination of mass growth rate has been done by several workers, there are only a few analyses of columnar type crystals based on field experiments until the present (Isono, *et al.* (1956), Ono (1970)).

Calculations have been made on the mass growth rate of columnar type ice crystals at the conditions of 650 mb, -35°C and water saturation, assuming diffusional growth of a prolate

spheroid (Mason, 1953) with actual values of the axial lengths derived from our data. The initial lengths of the crystals were taken as $10\text{ }\mu\text{m}$, and the axial ratio (c/a) was approximated by a straight relationship drawn by a solid line in Fig. 7(a). A bulk density of 0.9 for the crystal was adopted and the effect of ventilation was ignored. The calculated result is $dm/dt = 6.0 \times 10^{-10}\text{ gr}\cdot\text{sec}^{-1}$. This value coincides fairly well with that of the cold room experiments for column type crystal carried out by Mason (1953) of $6.25 \sim 7 \times 10^{-10}\text{ gr}\cdot\text{sec}^{-1}$. It is less than that of the field experiments for column type crystal carried out by Isono, *et al.* (1956) of $2 \sim 6 \times 10^{-9}\text{ gr}\cdot\text{sec}^{-1}$ referred by Ono (1970). The figures on the growth line in Fig. 7(a) are the growth time in minutes and they are comparable to the result of Isono, *et al.* (1956) referred by Ono (1970). The difference between both growth rates may depend on the following: in the case investigated by the authors, they adopted the mean values of the length of the crystals, but Isono worked in the presence of supercooled fog particles of a several tens to $50\text{ }\mu\text{m}$ in diameter.

9. Conclusions

Observations of diamond dust type ice crystals, carried out at around -35°C air temperature during the austral summer season at Amundsen-Scott South Pole Station, yield the following results.

Throughout the observation period, columnar type of ice crystals prevailed. However, occasionally more than half the number of ice crystals were plate types, including hexagonal, scalene hexagonal, pentagonal, rhombic, trapezoidal and triangular plates. Plate type crystals, larger than $200\text{ }\mu\text{m}$, prevailed under the conditions of air temperature around -35°C . This is an important to think the crystal habit comparing with T_a - $\Delta\rho$ diagram of Kobayashi (1961). Almost all shapes of the scalene hexagon reported by Klinov (1960) and studied by Yamashita (1973), were observed. No crystal of the initial stage of "peculiar shapes" reported by the authors (Kikuchi (1969, 1970, 1971), Kikuchi and Yanai (1971), Kikuchi and Hogan (1976)) was recognized in these stages of diamond dust. The number concentration of ice crystals varied cyclically, with peaks appearing at two hours intervals. Coincident with the time variation, there were characteristic increases of columnar type and of plate type crystals. When the number concentration of columnar type crystal decreased,

the length of c -axis of columnar type crystal among all ice crystals decreased; consequently, the axial ratio (c/a) decreased. When the number concentration of columnar type crystal increased, the length of c -axis of the crystal increased. Therefore, since the column type crystal grew more in length when the number concentration of ice crystals increased, it was expected that there was sufficient water vapor to grow the ice crystals in the atmosphere at the height of several tens to several hundred meters above the surface.

The length of a -axis of almost all columnar type crystals was shorter than $50\ \mu\text{m}$, and this result coincided with the observation result obtained by Isono, *et al.* (1956). The growth mode of columnar type crystals was fairly different from that of warm and cold regions column obtained by aircraft observations by Ono (1969). The mass growth rate was $6.0 \times 10^{-10}\ \text{gr} \cdot \text{sec}^{-1}$ and coincided with that of the cold room experiment by Mason (1953). However, it was less than that of the field experiments by Isono, *et al.* (1956).

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夏季の南極点基地で観測された細氷の性質

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1975年1月から2月にかけて、南極点基地で -35°C の温度条件下で観測された細氷時の氷晶の性質、特に氷晶の空間濃度の時間変化、結晶形、角柱状結晶の主軸の長さや軸比 (c/a)、成長様式等が解析された。

このような温度条件下では、一般的には角柱状の氷晶が卓越すると言われており、事実その通りであったが、時には氷晶の半数以上が不等辺六角形を含む、五角形、四角形、三角形等の角板状の氷晶が卓越した。空間濃度に約2時間程度の変動が認められたが、氷晶の空間濃度が減少すると氷晶は短い角柱状になり、逆に濃度が増加すると長い角柱になることがわかった。このことから雪面上わずか数10～数100 m 上空には氷晶を成長させるに十分な水蒸気があり、時として水飽和の層も認められた。

角柱の成長様式は Ono (1969) によって報告された温暖および寒冷領域の角柱とはかなり異なっていた。一方成長速度は $6 \times 10^{-10} \text{ gr} \cdot \text{sec}^{-1}$ で、Mason (1953) の低温室での実験の値に近かったが、Isono et al. (1956) -5°C の前後での野外実験の値よりは小さかった。

角板状の氷晶が成長したと考えられる温度の時間的・空間的な変動の範囲はせいぜい $-37^{\circ}\text{C} \sim -34^{\circ}\text{C}$ であり、Kobayashi (1961) の $Ta-\Delta\rho$ ダイアグラムから推定される -22°C 以下の温度領域での結晶形の鞘状、中空、無垢角柱とは異なっており、結晶習性に関しては新たな問題点が提起された。